



## Remarks on the chemical composition of highest-energy cosmic rays

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**Abstract:** We present arguments aiming to reconcile the apparently contradictory results concerning the chemical composition of cosmic rays of highest energy, coming recently from Auger and HiRes collaborations. In particular, we argue that the energy dependence of the mean value and root mean square fluctuation of shower maxima distributions observed by the Auger experiment are not necessarily caused by the change of nuclear composition of primary cosmic rays.

**Keywords:** chemical composition, air shower development, shower maxima fluctuations

### 1 Introduction

The identities of highest-energy cosmic rays remains still an open question. Possible conclusions on either protons or iron nuclei dominance in cosmic ray flux leads to problems [1]. Seeking to determine the nuclear identities of ultrahigh-energy cosmic-ray (UHECR) particles, the development of extensive air showers (EAS) of secondary particles in the atmosphere was extensively examined. The Auger collaboration [2] has determined both the shower maximum  $\langle X_{max} \rangle$  (the penetration depth in the atmosphere at which the shower reaches its maximum number of secondary particles) and the complementary observable  $\sigma(X_{max})$  (the root mean square fluctuation of  $X_{max}$  from event to event). Their results seem to indicate a transition, at primary energies of a few times  $10^{18}$  eV, from the flux dominated by protons to the one increasingly dominated at higher energies by iron nuclei. The HiRes collaboration [3] has analyzed event-by-event fluctuations of data in terms of the truncated fluctuation widths  $\sigma_T$  (the  $X_{max}$  distribution was truncated at  $2\sigma(X_{max})$ ), and reaches a different conclusion. We would like to present here arguments that the observed energy dependence of  $\langle X_{max} \rangle$  and  $\sigma(X_{max})$  by Auger experiment are not originated by the changes of nuclear composition of primary cosmic rays (cf., also, [4]) and that the highest-energy cosmic rays seems to be dominated by protons.

### 2 Inconsistency in the iron abundance

With the energy increase, the spectacular Auger data [2] show almost monotonic changes from proton composition towards iron one for both  $\langle X_{max} \rangle$  and  $\sigma(X_{max})$  observ-

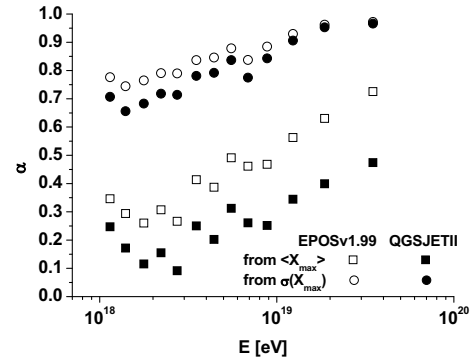


Figure 1: The energy dependence of relative abundance of iron in CR as extracted from  $\langle X_{max} \rangle$  and  $\sigma(X_{max})$  given by Auger experiment [2] (in frame of QGSJETII [10] and EPOSv1.99 [11] models).

ables. For  $\langle X_{max} \rangle$  such dependence can be easily interpreted by two component cosmic ray composition (with relative abundance of iron nuclei  $\alpha$  and contribution of protons  $1 - \alpha$ ), for which we expect

$$\langle X_{max} \rangle = (1 - \alpha) \langle X_{max} \rangle_p + \alpha \langle X_{max} \rangle_{Fe} \quad (1)$$

where  $\langle X_{max} \rangle_p$  and  $\langle X_{max} \rangle_{Fe}$  are the shower maxima for pure proton and iron nuclei, respectively. However for  $\sigma(X_{max})$  we have nonmonotonic dependence on  $\alpha$ ,

$$\sigma^2 = (1 - \alpha) \sigma_p^2 + \alpha \sigma_{Fe}^2 + \alpha(1 - \alpha) \left( \langle X_{max} \rangle_p - \langle X_{max} \rangle_{Fe} \right)^2. \quad (2)$$

For this reason the experimental data (with similar energy behavior) lead to quite different chemical composi-

tion, ranging from the proton dominated for  $\langle X_{max} \rangle$  to the iron dominated for  $\sigma(X_{max})$  (cf. Fig.1).

### 3 Importance of the first interaction point

Some remarks are in order at this point (cf. [5, 6, 7, 9]). Most of the charged particles in the shower are electrons and positrons coming from the electromagnetic subshowers initiated by photons from  $\pi^0$ -decay, with energies near the critical energy ( $\varepsilon = 81$  MeV in air). The mean depth of maximum for an electromagnetic shower initiated by a photon with energy  $E_\gamma$  is

$$\langle X_{max}^{em}(E_\gamma) \rangle = X_0 \ln(E_\gamma/\varepsilon), \quad (3)$$

where  $X_0 \approx 37$  g/cm<sup>2</sup> is the radiation length in air. A nuclear-initiated shower consists of a hadronic core feeding the electromagnetic component primarily through  $\pi^0$  production. In general, for an incident nucleus of mass  $A$  and total energy  $E$  (including protons with  $A=1$ ) the depth of maximum is expressed by

$$\langle X_{max}(E) \rangle = \langle X_{max}^{em}((E/A)(K/\langle n \rangle)) \rangle + \langle X_1 \rangle, \quad (4)$$

where  $\langle X_1 \rangle$  is the mean depth of the interaction with maximal energy deposition into shower (usually called the depth of the first interaction),  $K$  denote inelasticity and  $\langle n \rangle$  is related to the multiplicity of secondaries in the high-energy hadronic interactions in the cascade. If the composition changes with energy, then  $\langle A \rangle$  depends on energy and  $\langle X_{max} \rangle$  changes accordingly. The situation is, however, essentially more complicated. Whereas for a primary nucleus in which the energy is to a good approximation simply divided into  $A$  equal parts, in a hadronic cascade there is instead a hierarchy of energies of secondary particles in each interaction, and a similar (approximately geometric) hierarchy of interaction energies in the cascade. In this case  $\langle n \rangle$  has to be understood as some kind of "effective" multiplicity, which does not have a straightforward definition in general. For this reason the change of primary composition or the violation of Feynman scaling are widely discussed since many years. In addition to this, the inelasticity  $\langle K \rangle$  can itself be function of energy [15].

The probability of having the first interaction point of a shower,  $X_1$ , at a depth greater than  $X$  is

$$P(X_1 > X) \sim \exp(-X/\lambda), \quad (5)$$

where  $\lambda$  is the interaction length. In the case of perfect correlation between  $X_{max}$  and  $X_1$ , i.e., when fluctuations in the shower development were nonexistent, one could use directly the exponential distribution of showers with large  $X_{max}$  to calculate  $X_1$  and hence the proton-air cross section. However, intrinsic shower fluctuations modify relation between the depth of maximum distribution and the interaction length. This modification is typically expressed by a factor  $k = \Lambda/\lambda$  and leads to  $P(X_{max} > X) \sim \exp(-X/\Lambda)$ . The factor  $k$  depends mainly on how fast

is the energy dissipation in the early stages of shower evolution. In particular it is sensitive to the mean inelasticity and to its fluctuations. In general, a model with small fluctuations in secondary particle multiplicity and inelasticity is characterized by a smaller  $k$  factor than a model with large fluctuations. Under the assumption of similar fluctuations in multiplicity and inelasticity, a model predicting a large average number of secondary particles leads to smaller overall fluctuations of the cumulative shower profile of the secondary particles and hence to a smaller  $k$  factor.

In the absence of internal fluctuations, all showers would develop through the same amount of matter,  $\Delta X = X_{max} - X_1$ , between the first interaction point and the maximum. As a consequence, a perfect correlation between  $X_{max}$  and  $X_1$  would exist, and their distributions would have exactly the same shape, shifted by a constant  $\Delta X$ . In that case the slope of the  $X_{max}$  distribution,  $\Lambda$ , would be equal to the mean interaction length,  $\lambda$ . Intrinsic fluctuations in shower development (after the first interaction) affect the relation between the interaction length  $\lambda$  and the slope  $\Lambda$  that describes the exponential tail of the  $X_{max}$  distribution. The relation is often expressed with a  $k$  factor  $k = \Lambda/\lambda$ . For more properties of EAS and influence of shower fluctuations on studies of the shower longitudinal development see Ref. [5, 6, 7, 8, 9].

The effect of fluctuations in  $\Delta X$  is to broaden the correlation of  $X_{max}$  with  $X_1$ . However, we can roughly write that

$$\sigma(X_{max}) \cong \sigma(X_1) + \xi(\sigma(\Delta X)), \quad (6)$$

where  $\sigma(X_1) \propto \langle X_1 \rangle$  and the function  $\xi$  describes influence of shower fluctuations after the first (main) interaction point (notice that for the probability distribution given by Eq.(5) the fluctuation in  $X_1$  is  $\sigma(X_1) = \sqrt{\text{Var}(X_1)} = \langle X_1 \rangle$ , whereas for  $X_1$  interpreted as the main interaction point we have  $\sigma(X_1) = \langle X_1 \rangle / \sqrt{\kappa}$  where  $\kappa$  determines in which of the successive interactions of projectile particle the energy deposition to the shower is maximal). Because of Eq.(4), where  $\langle X_{max} \rangle = \langle X_{max}^{em} \rangle + \langle X_1 \rangle$ , we can construct observable in which influence of fluctuation of the first interaction point is strongly suppressed, namely

$$\begin{aligned} \langle X_{max} \rangle - \sigma(X_{max}) &\cong \\ &\cong \langle X_{max}^{em}((E/A)(K/\langle n \rangle)) \rangle + \xi(\sigma(\Delta X)). \end{aligned} \quad (7)$$

## 4 Results

In Fig.2 this observable is plotted for Auger [2] and HiRes [3] data in comparison with different models [10, 11, 12, 13]. To make the results from both experiment to coincide, the HiRes data are shifted by 10 g/cm<sup>2</sup> (in this case predictions from QGSJETII model are roughly the same for both experiment)<sup>1</sup>.

1. Notice that Auger compares the data with pure simulations. HiRes quotes data including all detectors effect and compare it

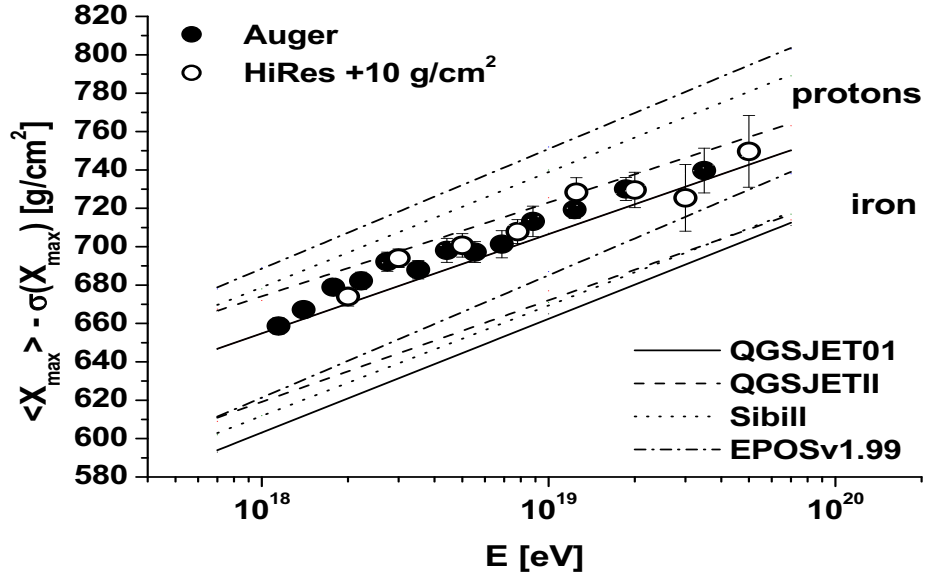


Figure 2:  $\langle X_{max} \rangle - \sigma(X_{max})$  as deduced from Auger data and  $\langle X_{max} \rangle - \sigma_T(X_{max})$  from HiRes data in comparison with different models. Notice that HiRes experimental data are shifted by  $10 \text{ g/cm}^2$  to make the model predictions for both experiment coincide.

Notice that  $\langle X_{max} \rangle - \sigma(X_{max})$  is still dependent on models and, in particular, it is sensitive to the chemical composition. Showers initiated by protons are seemingly different from those initiated by iron nuclei.

From Fig.2 we can learn that the chemical composition is not the origin of the effect observed by Auger experiment. Moreover, the experimental data fairly well coincide with the proton dominant primary composition. Within the toy model of primary composition (only two components: iron nuclei with relative abundance  $\alpha$  and protons with abundance  $1 - \alpha$ ) we can evaluate  $\alpha$  from  $\langle X_{max} \rangle - \sigma(X_{max})$  as given by Auger experiment. The results is shown in Fig.3. For the reference model QGSJETII the abundance of iron is roughly independent on energy ( $\alpha \simeq 0.05 \div 0.1$ ) and even for model EPOS v.1.99 [11], which leads to the maximal abundance of iron, it increases slowly with energy (varying in interval  $\alpha \simeq 0.15 \div 0.3$ ). The iron abundance shown in Fig.3 coincides with the one which can be estimated from HiRes data. The comparison of  $\alpha$  from Auger and HiRes data is shown in Fig.4. In the energy region  $2 \cdot 10^{18} \div 5 \cdot 10^{19} \text{ eV}$  the mean values of  $\alpha$ , evaluated from  $\langle X_{max} \rangle - \sigma(X_{max})$ , are equal  $\alpha = 0.08 \pm 0.01$  from Auger data and  $\alpha = 0.06 \pm 0.05$  from HiRes data (notice that HiRes data on  $\langle X_{max} \rangle$  result in comparable value,  $\alpha = 0.03 \pm 0.02$ ).

## 5 Possible interpretation

From Fig.2 we can learn that  $\langle X_1(E) \rangle$  gives the main contribution to the energy dependence of  $\langle X_{max} \rangle$  and  $\sigma(X_{max})$  observed experimentally. Two factors can affected energy dependence of  $\langle X_1(E) \rangle$ : the cross sec-

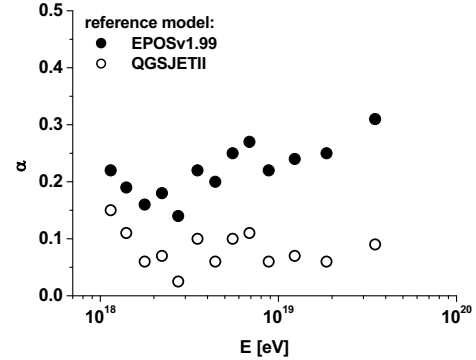


Figure 3: The energy dependence of relative abundance of iron in CR as extracted from  $\langle X_{max} \rangle - \sigma(X_{max})$  as given by Auger experiment and shown in Fig.2.

tion (interaction mean free path  $\lambda$ ) and the inelasticity  $K$ . Roughly,  $\langle X_1 \rangle = \lambda \cdot \kappa$ , where  $\kappa$  determines in which of the successive interactions of projectile the energy deposition to the shower is maximal. For a uniform inelasticity distribution in the maximal possible interval for a given  $\langle K \rangle$  one has  $\kappa \simeq 1 + 1.85(0.75 - \langle K \rangle)$ . The rapid increase of inelastic cross section in energies  $E > 10^{18} \text{ eV}$  cannot be excluded. In particular, if gluon saturation occurs in the nuclear surface region, the total cross section of proton–nucleus collisions increases more rapidly as a function of the incident energy compared to that of a Glauber-type estimate [14]. Although in [15] the decrease

to the models 'after' the detector simulation. Unfortunately that means that both approaches cannot be compared directly.

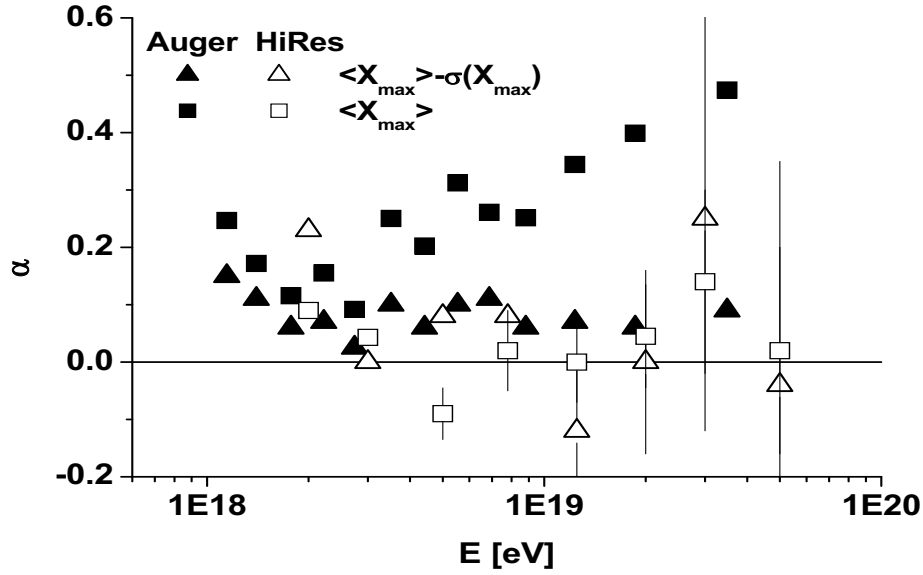


Figure 4: The energy dependence of relative abundance of iron in CR as seen from Auger and HiRes data (in the frame of QGSJETII model [10]).

of inelasticity  $\langle K \rangle$  with energies was discussed in lower energy region, its increase at energies  $E \sim 10^{18}$  eV is by no means excluded (cf. the percolation effects which in high energies leads to increase of inelasticity [16]). Both possibilities are questionable and require an abrupt onset of new physics beyond the standard model (notice however that here, the center of mass collision energy is about few hundreds of TeV, far beyond that can be studied at LHC). Taking into account the HiRes data (where  $X_{max}$  distribution was truncated at  $2\sigma$ ) we can learn that the tails of  $X_{max}$  distribution are crucial. For this reason, the role of biases due to the small statistics in analyzing CR data of highest energy remains an open question (cf. ref. [4]). It is interesting to note that the observable  $\langle X_{max} \rangle - \sigma(X_{max})$  is rather insensitive to the possible biases of the tail of  $X_{max}$  distribution [4].

## 6 Concluding remarks

To summarize, we conclude that the spectacular energy dependence of the shower maxima distribution reported by Auger collaboration [2] is not necessarily (or not only) due to the changes of chemical composition of primary cosmic rays. The observed effect seems rather to be caused by the unexpected changes of the depth of first interaction in energies above  $2 \cdot 10^{18}$  eV. They would require, however, an abrupt onset of some "new physics" in this energy region and are therefore questionable. We argue that it would be highly desirable to analyze the observable  $\langle X_{max} \rangle - \sigma(X_{max})$  in which fluctuations of the depth of the first interaction, as well as the possible biases of the tail of  $X_{max}$  distribution, are strongly suppressed. This observable still depends on the model of multiparticle pro-

duction and is sensitive to the chemical composition of the primary cosmic rays.

## References

- [1] B.Schwarzschild, *Physics Today*, 2010, **63**(5): 15-18
- [2] J.Abraham et al. (Auger Coll.), *Phys.Rev.Lett.*, 2010, **104**: 091101
- [3] R.U.Abbasi et al. (HiRes Coll.), *Phys.Rev.Lett.*, 2010, **104**: 161101
- [4] G.Wilk, Z.Włodarczyk, *J.Phys. G*, 2011, **38**: 085201
- [5] J.Alvarez-Muniz et al., *Phys.Rev. D*, 2002, **66**: 033011
- [6] M.Risse, *Acta Phys.Pol. B*, 2004, **35**: 1787-1797
- [7] R.Ulrich et al., *New J.Phys.*, 2009, **11**: 065018
- [8] R.Ulrich, R.Engel, M.Unger, *Phys.Rev. D*, 2011, **83**: 054026
- [9] J.Alvarez-Muniz et al., *Phys.Rev. D*, 2004, **69**: 103003
- [10] S.Ostapchenko, *Nucl.Phys. B (Proc.Suppl.)*, 2006, **151**: 143-146
- [11] T.Pirog, K.Werner, *Phys.Rev.Lett.*, 2008, **101**: 171101
- [12] N. N. Kalmykov, S. Ostapchenko, *Phys. At. Nucl.*, 1993, **56**: 346-353
- [13] E.J.Ahn et al., *Phys.Rev. D*, 2009, **80**: 094003
- [14] L.Portugal, T.Kodama, *Nucl.Phys.A*, 2010, **837**: 1-14
- [15] Z.Włodarczyk, *J.Phys. G*, 1993, **19**: L133-L138
- [16] J.Dias de Deus et al., *Phys. Rev. Lett.*, 2006, **96**: 162001